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Computer Analysis of Fuel Cell Power Systems Performance for Naval Applications

by
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ABBREVIATIONS

ATM	Atmosphere
ATR	Auto thermal reformer
BOP (B.O.P.)	Balance of plant
BTU (B)	British Thermal Unit
CAD	Computer aided design
COMP	Compressor
CORP	Corporation
C_p	Heat capacity (constant pressure)
DEG	Degree
F	Fahrenheit
FLO	Flow
FO	Fuel Oil
ft^2	Square foot
ft^3	Cubic foot
GAL	Gallon
GEN	Generator
H	Enthalpy
HDS	Hydro desulfurizer
HR	Hour
HRS	Hours
HX	Heat exchanger
in^2	Square inch
k	Killo
kW	Killowatt
kWh	Killowatt hours
LB	Pound
LOX	Liquid oxygen
M	Mole
MAT'L	Material
MCFC (MC)	Molten carbonate fuel cell
MPH	Mole per hour
MW	Megawatt
P	Pressure
PAFC (PA)	Phosphoric acid fuel cell
PEM	Polymer exchange fuel cell
REFMR	Reformer
SAT	Saturator
SOFC (SO)	Solid oxide fuel cell
SWBS	Ship work breakdown structure
S/O	Selective oxidized
T	Temperature
TURB	Turbine
VS	Versus

ABSTRACT

This report demonstrates the use of computer programs to model and analyze fuel cell power systems for ship applications which utilize hydrocarbon fuels. Programs available include those for Molten Carbonate (MCFC), Phosphoric Acid (PAFC), and Polymer Exchange Membrane (PEM). The PEM system was chosen as an illustrative example because the program for the PEM model is the most comprehensive of the available programs. It has been recently employed extensively in a ship impact study conducted by the Carderock Division, Naval Surface Warfare Center (CDNSWC).

The development of a 2500kW PEM fuel cell power system is described in detail beginning with functional input requirements and ending with a complete physical model. The model includes the size and weight of all major power plant components required to produce direct current electric power with diesel fuel. The fuel cell system weights and volumes are compared to state-of-the-art gas turbine and diesel engine generators. Fuel utilization curves are generated and compared with typical equivalent engine generator systems.

The output of each phase of development is exhibited as the program is run. For example: the system architecture, material balances, energy balances, detailed heat exchanger utilization and design data, acquisition and life cycle cost estimates, component weights and volumes, and off-design performance (fuel rate versus per cent rated load data). A three dimensional computer model of the system is drawn from the generated data showing the major components in relative positions using AutoCad™. This model can be utilized in other AutoCad™ compatible programs to demonstrate the spatial arrangement of components within the ship and to estimate centers of gravity and moments.

Recommendations stemming from this study include: creating a module for SOFC technology; and modifying the existing modules to include bottoming cycles, optimization for maximum water recovery, and updated heat exchanger designs and materials.

ADMINISTRATIVE INFORMATION

This report is submitted in partial fulfillment of Milestone 1, Task 4 of the Mechanical Power and Auxiliary System Project (RN21E42). The work herein was sponsored by the Office of Naval Research (ONR 4524) and performed by the Fluid Systems and Machinery Analysis Branch, Code 824, of the Power Systems Department, Machinery Research and Development Directorate, Naval Surface Warfare Center, Carderock Division, Annapolis Detachment. The computer programs referred to in this report were developed by Analytic Power Corporation under NSWC Contracts N61533-89-C-0008, N61533-90-C-0043 and N61533-91-C-0101. The authors also acknowledge NAVSEA 03R17 for sponsoring fuel cell studies which utilized these programs.

INTRODUCTION

Definition

A fuel cell is an electrochemical device, similar to a battery, which converts fuels such as natural gas or heating oil to electricity without combustion and without generation of noise. Fuel cell power systems have no moving parts except for a few pumps and blowers. Electric power generators are consist of many fuel cells connected together to form large arrays as required to meet the power demands.

Fuel cell advantages in naval applications

In preliminary ship power studies[1], fuel cell power plants have shown distinct advantages over conventional maritime gas turbines and diesel plants. These advantages include higher efficiency and reduced weight and volume. In addition to these benefits, it was also predicted that ship service power and propulsion power installations based on a fuel cell power plant design, and incorporated into a Navy vessel's design, may realize cost savings as the price of less polluting fuels and fines levied for air pollution increase in the future.

Advantages Unique to Fuel Cells

The minimum amount of moving components, intrinsic non-magnetic materials of construction, and inherent high thermal efficiency combine to give the Navy three advantages not met by any other power generating system:

- Stealth
- High Fuel Economy (lower fuel costs/longer missions)
- Essentially Zero Pollution

Overall Thermal Efficiency

As fuel cells are electrochemical devices, not heat engines, they are not subject to Carnot efficiency limitations, and can achieve very high efficiencies at moderate temperatures with appropriate design. A conservatively designed fuel cell power plant can exceed gas turbine and diesel efficiencies by several percentage points. An even more important benefit in efficiency is attained in the off design case. Standard Navy practice requires a backup generator to be at idle in case of the failure of the prime power unit. Two ship service power plants are therefore usually run at half power. Gas turbine and diesel engines running at half power lose efficiency. The efficiency of fuel cells, on the other hand, increases as loads are reduced from full load.

The effect of off-design operation on overall thermal efficiency for various engine generator systems using diesel fuel is compared in Figure 1. The Allison 501-K34 gas turbine, presently used as the ship service generator on many Navy ships has a design point efficiency of roughly 33%; this drops to about 25 % at half power. By comparison, the efficiency of a 2500 kW PEM system, the uppermost curve on Figure 1, is projected to be 5 percentage points higher than the intercooled regenerative (ICR) gas turbine engine generator, and 17 percentage points higher

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[1] Boughers, Ward, et al., *The Assessment of Fuel Cell Power Plants for Surface Combatants: Final Report*, CARDIV-TM-(not numbered), in publication.

than the LM2500 engine generator. The efficiency of the PEM system is very flat over the load range.

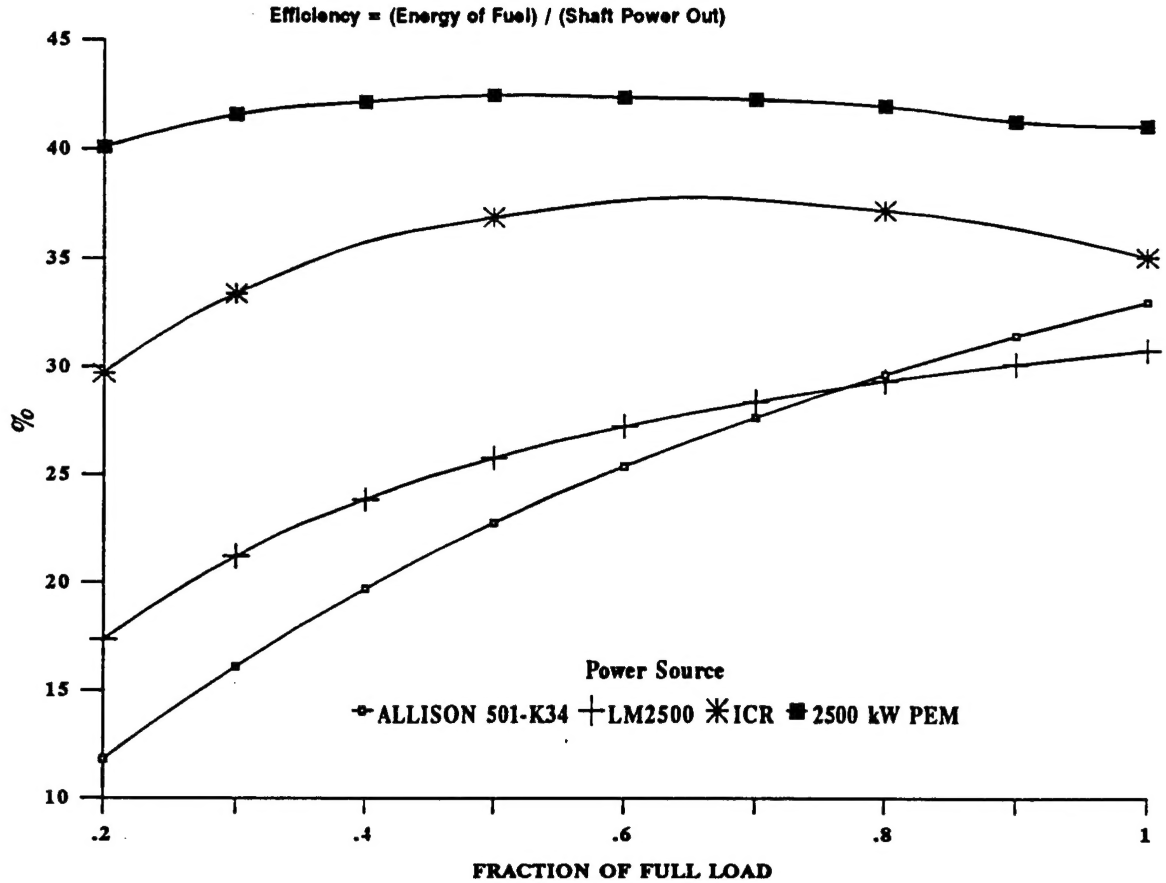

Figure 1. Comparison of the effect of load on performance.

<u>System Weight and Volume</u>

Initial studies indicated that fuel cells power plants by themselves can be made lighter than comparable gas turbines or diesel plants. Further studies indicated that in the context of the entire power system and support equipment, these savings will be even more dramatic. Support equipment includes such things as exhaust and inlet stacks, gearing, foundations, operating fluids and lubricants, and fuel service system. Based on the Ship Breakdown Structure (SWBS) for an Arleigh class vessel, the gas turbine engines themselves make up only a small part of the total weight, volume and cost of a main propulsion or ship service power system.

System Cost

It is unlikely that fuel cell systems are competitive today with equivalent engine generator systems strictly on a cost basis at the present time due to the immature nature of the technology. Some inherent fuel cell design features, however, indicate significant cost saving in the immediate future, given the present direction of environmental and energy policies.

Modular design, low thermal emission, and low pollution allow fuel cell systems to be placed in inhabited spaces and arranged to suit the space available. This modular nature also permits great flexibility in meeting the inevitable increasing power demands. Instead of designing a new engine or modifying an existing engine, the fuel cell system power can be increased by simply adding modules. It is beyond the scope of this report to estimate these cost savings, but they should be significant.

Fuel cell systems operate on hydrogen. The source of this hydrogen is insignificant except as it affects storage and handling. Surface naval requirements dictate systems which can operate with diesel fuel while submersibles might use a synthetic fuel such as methanol. In all cases a processor to convert the fuel to hydrogen is an integral part of the system. This contrasts with some utilities in the United States and Japan which use fuel cells operating with natural gas, kerosene, coal gas, and similar fuels. The design and complexity of a fuel cell power generating system, and, therefore, the costs, depends on the application and the type of fuel available.

As more synthetic and renewable fuels become available and possibly mandatory due to air quality requirements in the future, the cost effectiveness of fuel cell power systems aboard ships will increase dramatically because the stacks will not be effected or require modification.

SCOPE

The Center has been extensively involved in the design and analysis of fuel cell power systems for Naval applications and is presently investigating the impact of various systems on ship design. Toward this end, a suit of computer aided design programs were developed under contract from the Analytic Power Corporation[2]. These programs assist engineers in the design of complete power plants based on the net power production required. Data from these programs can be used to analyze the effects of parameter modifications on the plant weight, size, and efficiency. The data can also be used to produce 3-dimensional computer models of specific power plants, within which, components may be visualized and spatially arranged for available spaces, such as; ship engine rooms, auxiliary spaces, and an infinite number of other arrangements useful in making ship impact assessments.

This report endeavors to demonstrate the power of the Analytic Power Corp. computer programs in designing a broad range of fuel cell power systems. A specific example of designing a 2500 kW PEM system, concluding with the production of a 3-dimensional AutoCad® model is employed to illustrate the result of the process.

[2] Friedhoff and Bloomfield, *ANALYTIC POWER CORPORATION FINAL REPORT C055 FUEL CELL SYSTEMS STUDIES*, Contract No. N61533-91-C-0101, April 1992.

COMPUTER PROGRAM DESCRIPTION

The following is an example of using a typical design program using the Analytic Power Corp. modules for PEM fuel cell power systems. The source modules include the following sub modules which are automatically concatenated during program execution of the main module:

- DTRC7R5 .BAS Main program, fuel cell and stack design module, and sub program manager
- FC_TAP .BAS Design data storage and handling module
- HXNET1 .BAS Heat/energy balance
- HXNET2 .BAS Heat management architecture
- HXNET3 .BAS Heat exchanger and condenser design module
- ECON7 .BAS Cost estimating module
- WT-VOL7 .BAS Balance of plant (reformer, shift converter, desulfurizer, and saturators) design, and heat exchanger and condenser weight and volume sizing
- DTRC7_OD.BAS Off-design performance prediction.

The modules are written in BASIC (Quick Basic 2) and are compiled to executable form from which they are executed.

Overall Program Operation

The design of fuel cell systems utilizing an auto thermal reformer assumes the overall fluid flow pattern shown in Figure 2. Figure 3 shows the diagram which appears on the computer screen as the program executes. The numerals in parenthesis represent nodes with which the computer determines the material and energy balances.

The system operation can best be comprehended by following the flow schematic in Figure 3 while reading the description below.

Anode Operation. Fuel (node 1) is pumped to system pressure, pre-heated and vaporized in the ATR. At the ATR inlet (node 3) fuel vapor is mixed with spent air from the cathodes of the fuel cell stack containing unreacted oxygen. This oxygen is used to burn some of the fuel creating heat for the thermal reforming process which liberates hydrogen (H_2) from the fuel and produces carbon dioxide (CO_2) and carbon monoxide (CO). Sulfur is converted to hydrogen sulfide (H_2S) in the highly reducing atmosphere. The hot reformate enters the heat exchanger (node 4) giving up much of its heat to the cooler incoming air and then enters a system of zinc oxide (ZnO) beds which adsorbs the H_2S. The desulfurized gas enters the shift converter (SHIFT) (node 25) where CO, reacts with steam producing CO_2 and H_2. The hydrogen rich stream passes through a selective oxidizer (SO) where any remaining CO is converted to CO_2. The gas then enters the anode saturator (SAT) where it is contacted with water (node 26 to 27) before entering the anode manifold of the fuel cell stack (node 5). In the anode flow fields of the cells, hydrogen is electro-chemically converted to hydrogen ions which migrate through the membrane electrolyte to the cathode flow field. If the computer deems conditions to be favorable, excess water may be condensed from the anode gases prior to exiting at node 6. The spent anode gas is mixed with compressed inlet air in a catalytic burner where the remaining hydrogen is oxidized. This reaction raises the temperature of the exhaust (node 14) for operation of the turbocharger. The exhaust is then ducted to the atmosphere.

Cathode Operation. Ambient air entering the turbocharger (node 7) is compressed to the operating pressure (node 8) designated in the set up parameters.

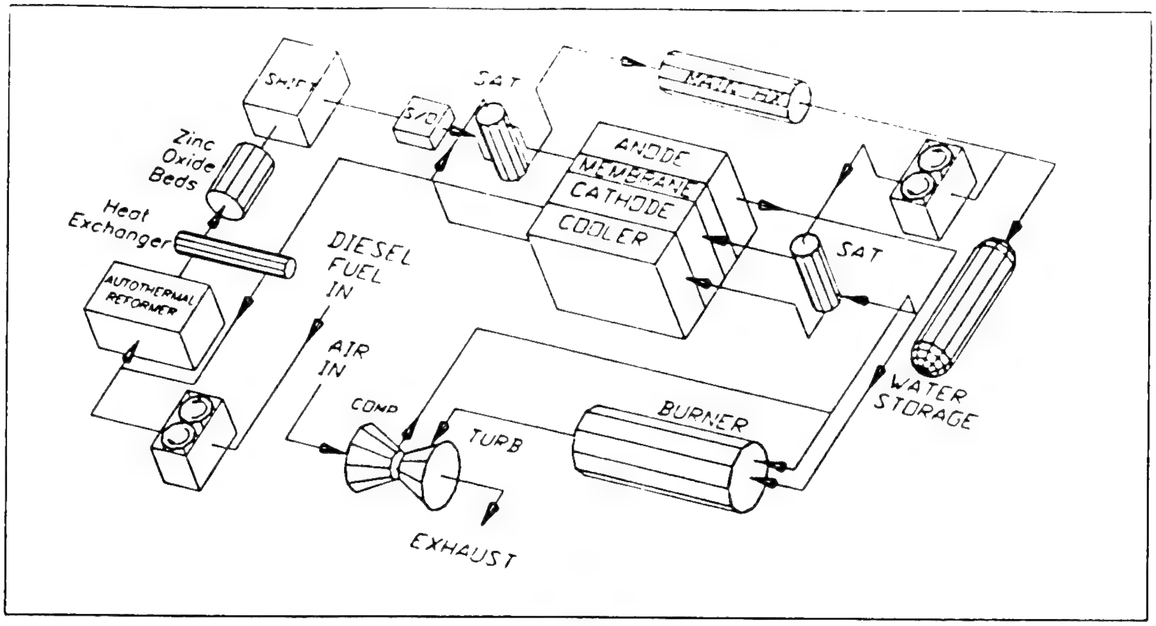

Figure 2. Schematic of a typical PEM fuel cell power system using auto thermal reforming.

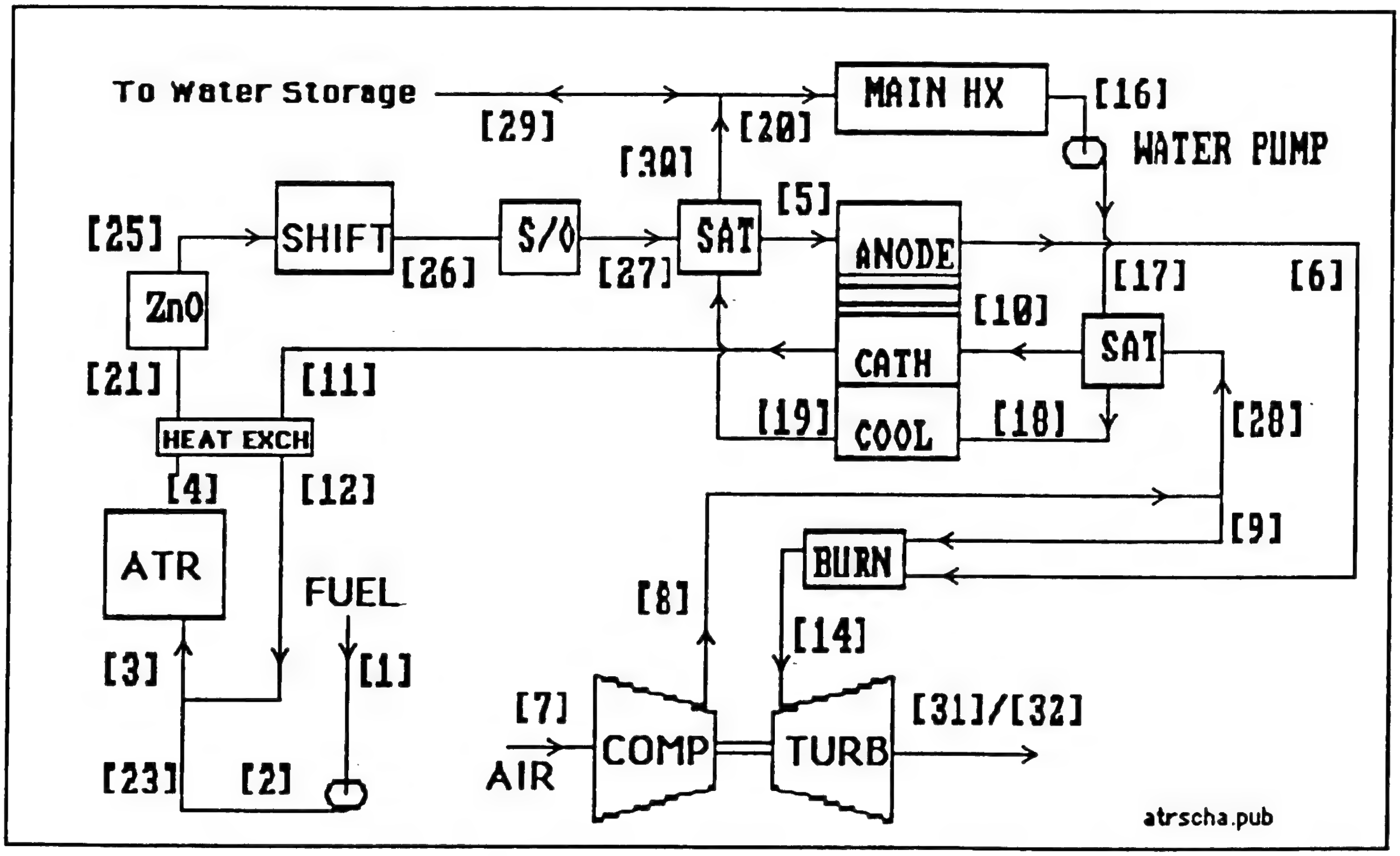

Figure 3. Computer generated diagram of flow schematic showing nodes used in system design and analysis.

The pressurized air is saturated with water prior to entering the cathode manifold (node 10). As air passes through the cathode flow fields in the cells, oxygen is reacted electrochemically with hydrogen ions migrating through the membrane from the anode, producing water. Water produced in the fuel cell reaction is removed from the air stream in a sea-water cooled condenser (not shown on the schematic) and retained in the water management system (node 29). The air (node 11) is heated in the heat exchanger with gases from the ATR before entering the ATR (node 12).

Water management system. The water produced in the cells is essentially pure. Water is circulated through the cathode saturator (node 17) where it contacts the inlet air and then to the cooling manifold of the cell stacks. The temperature of the water is increased as it passes through the flow fields of the cells and removes excess heat. The heated water (node 19) then enters the anode saturator where it saturates the hydrogen rich anode stream. Water remaining in the loop (node 20 to 16) is cooled in a ship raw water heat exchanger. This accounts for most of the heat rejection in the system.

Operation of the Design Program.

The following gives a description of the execution of the computer programs in the design and analysis of a fuel cell power system. Figure 4 shows an algorithm of the overall program functions in block form to simplify explanation.

Input data. The operator begins execution by running "DTRC7R5". The first screens contain the initial parametric data which the operator may change as required. The following parameters are variable.

- Net power, kW (in most modules)
- Mechanical efficiency, percent (pumps, blowers, etc.)
- System pressure, Atm
- Cell voltage (affects efficiency and current density)
- Cell inlet temperature, deg F
- Hydrogen utilization, percent
- Water to carbon ratio in reformer (affects reformer efficiency)

First approximations. Average cell performance is predicted form the input conditions applied and the polarization curve data of the system involved. The polarization curves vary greatly with fuel cell technology. Then the stack performance is computed and compared with the required net power. If the comparison is not within design parameters, adjustments to the number of cells, cells per stack, and cell active area is modified and the process reiterated.

Material and energy balance. When the stack design meets the required parameters the program begins determination of the overall material balance. To obtain the necessary balance the size and performance of the fuel processing equipment is modified. When a balance is obtained, an energy balance is attempted. To attain a correct balance the gross power is modified and the cell and stack design is reiterated. These processes continue until both the material and energy balances.

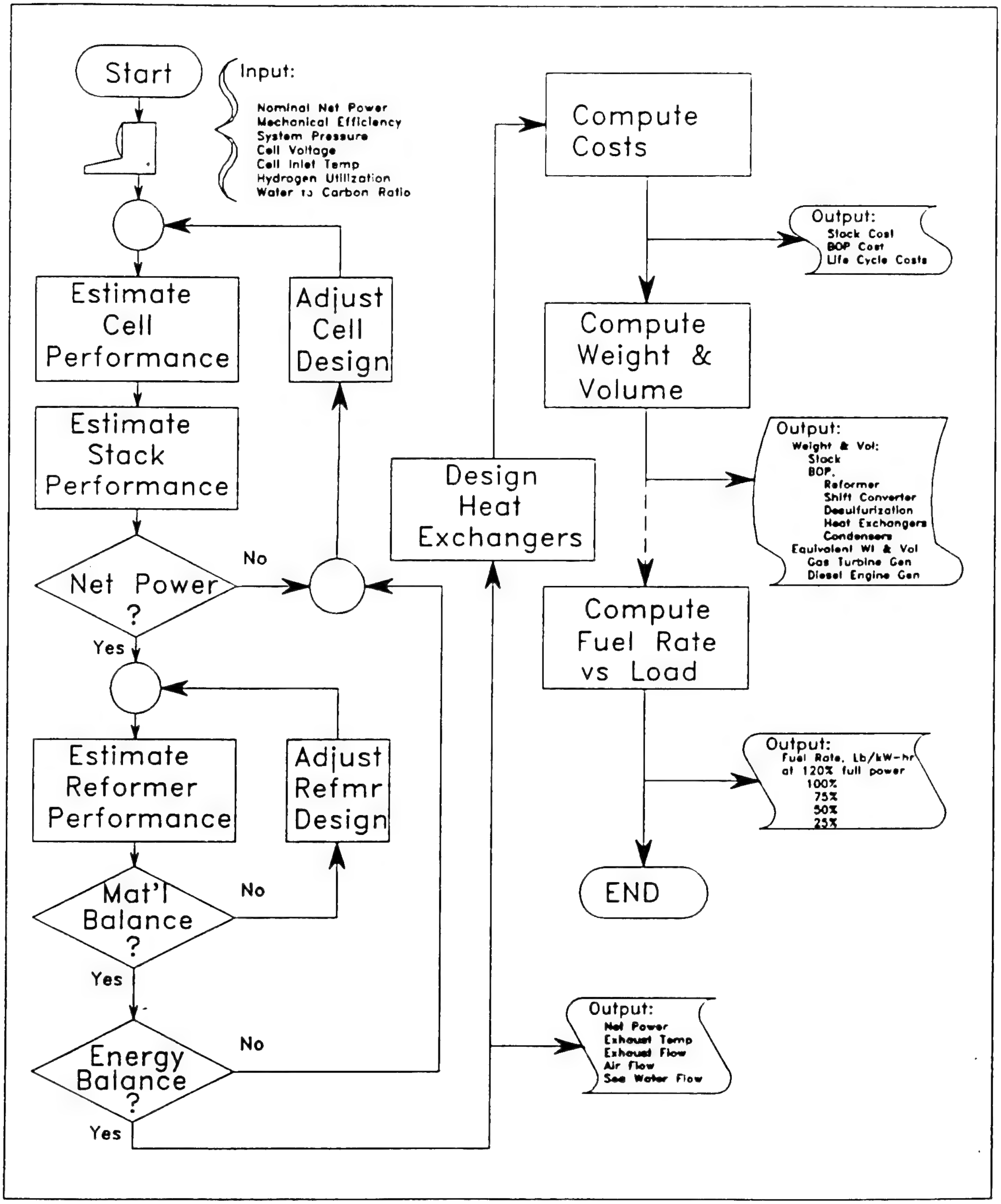

Figure 4. Algorithm for a typical design program, DTRC7-R5.

At this point, the following outputs are available:

- Net power
- Exhaust temperature
- Exhaust flow rate
- Exhaust composition
- Air flow rate
- Sea water flow rate

Heat exchanger design. The operation of the heat exchanger design sub program is extremely complex and well beyond the scope of this report. It is sufficient to state that the program designs appropriate heat exchangers and arranges their placement in the flow schematic for maximum efficiency. A diagram of the heat exchanger system is available to the operator on demand.

Cost estimates. The cost estimation sub program is straight forward and is very comprehensive. Cost estimates include acquisition costs, developmental costs of various contingencies from prototype to final production units, operational costs, and costs involved in buying (eg. cost of money, etc.), installation, and maintenance (40-year depreciation). This sub program was written by Analytic Power Corp. for the electric power industry applications and includes information not particularly applicable to Navy needs. Data available and usually recorded at this point includes:

- Stack cost
- Balance of plant cost
- Life cycle cost

Weight and volume calculations. The calculation of hardware weight and volume is straight forward and involves using data generated in the design sub programs to determine the volume of various equipment. A table of weight factors and material densities are used in conjunction with standard practices with regard to pressure vessel and heat exchanger design to establish the final weight data. The following data is available:

- Weight and volume of;
    - Stack
    - BOP,
        - Reformer
        - Shift converter
        - Desulfurization equipment
        - Heat exchangers
        - Condensers
- Equivalent weight and volume
    - Gas turbine generator set
    - Diesel engine generator set

Off design data. After completion of the initial design program, the performance prediction module can be executed to obtain the performance of the design at various power levels. This module is essentially a modified version of DTRC7R5.bas where the size of hardware is fixed and the temperatures, pressures and flow rates are allowed to vary according to the applied load. The most important information from this module is the fuel rates at selected loads which can be used to obtain specific fuel consumption curves.

TYPICAL FUEL CELL POINT DESIGNS

Point design modules for PEM, MCFC, and PAFC fuel cell systems were developed and updated by Analytic Power Inc. under Navy contract (see page). Recently they were used to produce designs and data for a ship impact study where the beneficial assets of fuel cells could be evaluated when applied to a theoretical surface ship. Some examples of these point design data spread sheets for PEM, PAFC, and MCFC systems are shown in Appendices A, B, and C, respectively.

The following example of a typical point design uses the PEM technology. PEM technology was chosen because it represents the technology for which the most comprehensive analytic programs have been developed at present. Software facilities now include all the existing fuel cell technologies except solid oxide (SOFC). SOFC development is in the early stages at this time and a viable model for both planar and tubular technologies will be developed in the near future.

<u>The System Design Program, DTRC7-R5.</u>

At the start of the design program the operator must supply the following initial data:

- automatic or manual operation
- name of set-up file
- graphic displays on or off

For this example, automatic operation is proper. Manual operation allows the on-line observation and alteration of many parameters and is best suited for initial runs or trouble shooting if computer errors occur. The set-up files contain initial parameters which will become the default values. It may be edited to suit a particular set of initial conditions to speed up future data entry. Most of these values may be reset or defaulted as the program continues. Figure 5 shows a composite screen of initial data for a 2500 kW system.

```
INPUT POWER PLANT DATA                          HIT <CR> TO SELECT DEFAULT VALUE
--------------------------------------------------------------------------------
POWERPLANT SIZE, kW            2500    | REFORMER INLET degF              1200
INVERTER EFFICIENCY - %        1       | REFORMER EXIT degF               1550
MECHANICAL EFFICIENCY - %      .95     | REFORM OFFSET degF               150
SYSTEM PRESSURE -  atm         6       | SHIFT OFFSET degF                50
--------------------------------------------------------------------------------
DATA FOR DIESEL FUEL:                           HIGHER HEATING VALUE = 19350
LOWER HEATING VALUE = 18300  BTU/lb             AVERAGE MOLECULAR WT = 204
   WATER TO CARBON RATIO                                    3.5  INPUT UPDATE?
--------------------------------------------------------------------------------
PEM FUEL CELL:
   INPUT CELL VOLTAGE - volts                               .7   INPUT UPDATE?
   INPUT ANODE INLET TEMPERATURE - deg F                    220  INPUT UPDATE?
   INPUT CATHODE INLET TEMPERATURE  - deg F                 220  INPUT UPDATE?
   INPUT OXYGEN UTILIZATION                                 .6   INPUT UPDATE?
   INPUT HYDROGEN UTILIZATION                               .85  INPUT UPDATE?
   INPUT CELL TEMPERATURE                                   238  INPUT UPDATE?
   INPUT REFORMER PRESSURE                                  6    INPUT UPDATE?
```

Figure 5. Initial data screen display, DTRC7-R5.

Figure 6 shows a summary of the initially assumed conditions used by the computer prior to entering the material/energy balance routines as it appears on the operator's console.

DTRC7-R4 PLANT PERFORMANCE DATA			
OVERALL EFFICIENCY	37.7 %	CELL	
		CURRENT DENSITY	953.5 asf
POWER:		CELL VOLTAGE	0.700 volts
NET	2512.1 kW	OPEN CIRCUIT (dH/nF)	1.239 volts
GROSS	2644.4 kW	CELL AREA	3961.7 ft2
FUEL CELL	2644.4 kW		
INVERTER	0.0 kW	ENERGY IN	6.3E+06BTU/HR
PARASITE	132.2 kW	H(7) AIR IN=	3.0E+06BTU/HR
		H(1) FUEL IN=	-1.7E+03BTU/HR
		OIL HTR IN=	5.2E+05BTU/HR
UTILIZATION:		COMP SHAFT IN=	2.8E+06BTU/HR
FUEL	0.850		
		ENERGY OUT=	6.1E+06BTU/HR
OXYGEN	0.717	H(32) GAS OUT=	-1.9E+07BTU/HR
		P(GROSS) OUT=	9.0E+06BTU/HR
TEMPERATURE:		MAIN HX OUT=	5.0E+06BTU/HR
ANODE INLET	262.2 deg F	TURB SHAFT OUT=	6.4E+06BTU/HR
CATHODE INLET	244.7 deg F	MAIN COND OUT=	6.4E+06BTU/HR
CELL EXIT	261.0 deg F	ATR REGEN EFF	0.89

Figure 6. Initial conditions display screen.

After the material/energy balance is complete, it is possible to obtain a listing of the temperatures, pressures, and composition at almost all nodes (refer to Figure 3). The entire listing is too comprehensive to include in this report as it produces several pages in fine print, however Figure 7 contains a truncated sample of the node array produced while running this design program demonstration.

MICROFLO NODE ARRAY
MOLE FRACTIONS %

NODE	1	2	3	4	5	6	7	8	9	10
H2	0.000	0.000	0.000	16.714	17.571	3.098	0.000	0.000	0.000	0.000
H2O	0.000	0.000	40.804	26.453	34.959	41.097	0.000	0.000	0.000	22.680
CH4	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000
CO	0.000	0.000	0.000	4.364	0.000	0.000	0.000	0.000	0.000	0.000
CO2	0.000	0.000	0.000	5.675	8.340	9.804	0.000	0.000	0.000	0.000
O2	0.000	0.000	4.080	0.000	0.000	0.000	20.950	20.950	20.950	16.198
N2	0.000	0.000	54.338	46.793	39.129	46.000	79.050	79.050	79.050	61.121
No.2 FO	100.000	100.000	0.777	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL	5.821	5.821	748.940	869.704	1040.042	884.705	797.269	797.269	282.455	665.826
T DEG F	70	70	1298	1550	262	261	70	575	575	245
P ATM	6.000	47.619	6.000	6.000	6.000	6.000	1.000	6.000	6.000	6.000
H BTU/HR	-1.606E+03	-1.373E+05	-2.021E+07	-2.021E+07	-4.648E+07	-4.725E+07	2.963E+06	5.806E+06	2.057E+06	-1.213E+07
S BTU/HR F	-1.333E+02	-4.133E+02	3.989E+04	4.539E+04	4.594E+04	3.960E+04	3.553E+04	3.645E+04	1.291E+04	2.936E+04
CP B/HR F	3.982E+02	5.696E+02	7.980E+03	7.633E+03	7.939E+03	6.861E+03	5.553E+03	5.751E+03	2.038E+03	4.847E+03

Figure 7. Sample node array of the system design module DTRC7-R5.

Heat Exchanger Modules, HXNET-1B, HXNET-2B, and HXNET-3B.

The program automatically starts the heat exchanger design programs after conclusion of the system design module DRTC7-R5. The operator has the option of automatic or manual control. Automatic control is preferable with the manual mode chosen only for special conditions or trouble shooting in case of program error. The operator can change or default the heat exchange coefficients for nine models depending on the heat transfer technology. Most of the default coefficients are for a standard shell and tube arrangement. The exception is the hot gas heat exchanger (heat exchanger #(1) in Figure 8), which is a plate type.

During the operation of this module the energy balance is revisited and a special routine selects and positions heat exchangers for maximum efficiency. At the conclusion a system map similar to that shown in Figure 8 is produced showing the position of each numbered heat exchanger relative to the nodes. The design data for each heat exchanger is manually selectable and appears similar to the sample shown in Figure 9.

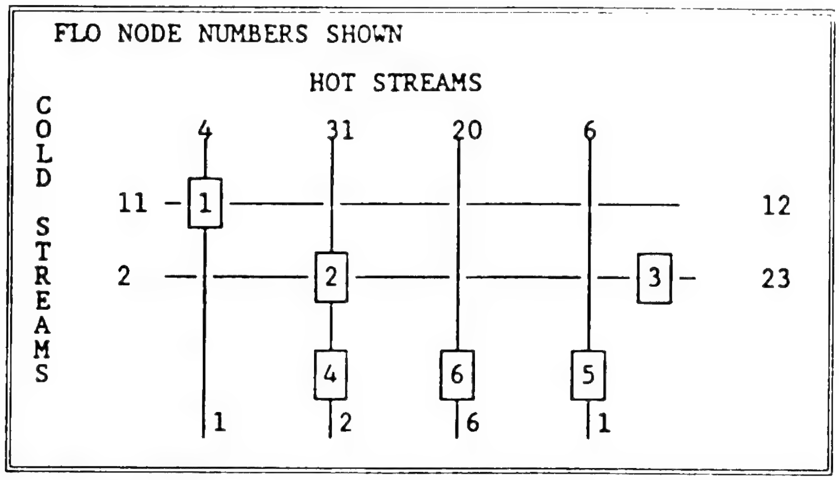

Figure 8. Heat exchanger design output matrix.

During the heat exchanger design program execution, the operator is given the opportunity to bypass the graphics mode. This is a preferred choice when generating several design variants where the basic heat exchanger layout would not be expected to change with input requirements. At the conclusion of the heat exchanger programs all pertinent data is automatically recorded in a disk file for use in the subsequent weight/volume and off-design programs.

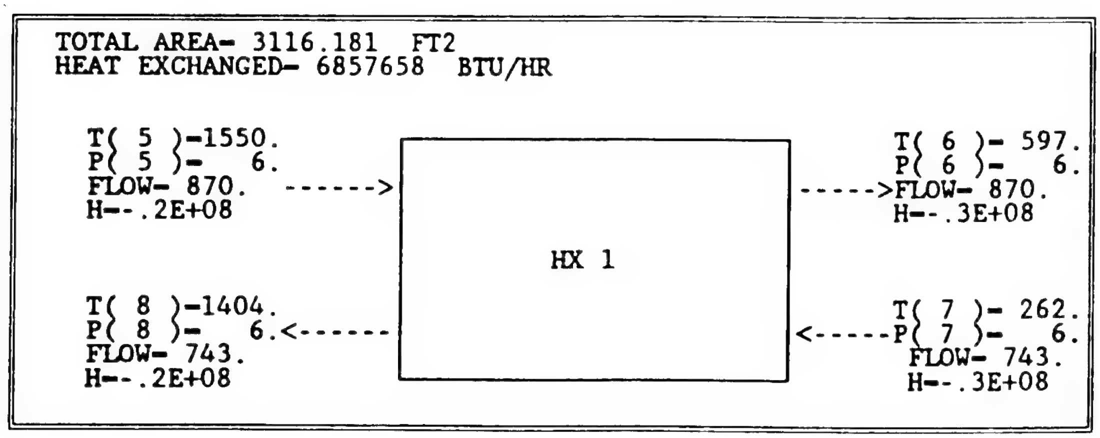

Figure 9. Typical heat exchanger design output screen.

Cost Estimating, ECON7.

The cost module is quite comprehensive being based on the requirements of power production industry and includes many aspects not pertinent to naval applications. It is arranged in a logical procedure and draws from an established

data base. Several screens of data are presented from which the operator can glean the information pertinent to his requirements.

The operator has the opportunity to modify several cost parameters, the first of which is the cost of the cell components in dollars per square foot of cell hardware. This is very important in light of the ever decreasing costs as development continues. As the program executes many other screens are presented with various options for the operator. A typical set of screens is shown in Figures 10 through 13.

The first screen, Figure 10, allows the operator to vary the process contingency factors of selected cost items based of the maturity of the technology. Suggested percentages are listed at the bottom. For this example, all items will be assigned the default value for "small pilot plant data" of 20 percent.

```
     ASSIGN CONTINGENCIES
  FUEL CELL POWER SECTION       $    478,995.  <
  FUEL PROCESSING               $    373,063.
  CONDENSER EQUIPMENT           $        413.
  HEAT EXCHANGERS               $     35,206.
  GAS CLEANUP                   $     77,884.
  POWER CONDITIONING            $          0.
  LOX PRODUCTION                $          0.
  TURBINES & COMPRESSORS        $    126,423.
  STEAM TURB. & GEN.            $          0.
  INSTRUMENT. & CONTROL         $    136,498.
  STRUCTURES & PLUMBING         $    136,498.
  GENERAL FACILITIES            $     68,795.

  PROCESS CONTINGENCIES
     NEW PROCESS - LIMITED DATA.... 40  %
     CONCEPT - BENCH SCALE DATA.... 30  %
     SMALL PILOT PLANT DATA........ 20  %
     FULL SCALE PLANT OPERATED.....  5  %
     COMMERCIALIZED................  0  %
  ASSIGN PROCESS CONTINGENCY  20  %?                 ANALYTIC POWER CONTINGENCIES
```

Figure 10. Example of process contingency cost screen.

After this is accomplished, a second screen is presented allowing the operator to assign an overall project contingency. In this example, the default value for a "preliminary" plant with a value of 15 percent will be accepted.

```
     ASSIGN CONTINGENCIES
  FUEL CELL POWER SECTION       $    478,995.   $     574,794.
  FUEL PROCESSING               $    373,063.   $     447,675.
  CONDENSER EQUIPMENT           $        413.   $         413.
  HEAT EXCHANGERS               $     35,206.   $      35,206.
  GAS CLEANUP                   $     77,884.   $      77,884.
  POWER CONDITIONING            $          0.   $           0.
  LOX PRODUCTION                $          0.   $           0.
  TURBINES & COMPRESSORS        $    126,423.   $     126,423.
  STEAM TURB. & GEN.            $          0.   $           0.
  INSTRUMENT. & CONTROL         $    136,498.   $     136,498.
  STRUCTURES & PLUMBING         $    136,498.   $     136,498.
  GENERAL FACILITIES            $     68,795.   $      68,795.

  PROJECT CONTINGENCIES
     SIMPLIFIED DESCRIPTION......... 30  %
     PRELIMINARY.................... 15  %
     DETAILED....................... 10  %
     FINALIZED...................... 5  %

  ASSIGN PROJECT CONTINGENCY  15 %?
```

Figure 11. Example of project contingency cost screen.

After all contingencies are assigned, a summary of the costs, Figure 12, is displayed. The operator may extract selected data from this display, or the program may be amended to allow automatic recording of the selected data in a data file.

	CAPITAL COST	CC+PROC CONT.	CC+ALL CONT.
FUEL CELL POWER SECTION	$ 192.30 /KW	$ 230.76 /KW	$ 265.37 /KW
FUEL PROCESSING	$ 149.77 /KW	$ 179.73 /KW	$ 206.68 /KW
CONDENSER EQUIPMENT	$ 0.17 /KW	$ 0.17 /KW	$ 0.19 /KW
HEAT EXCHANGERS	$ 14.13 /KW	$ 14.13 /KW	$ 16.25 /KW
GAS CLEANUP	$ 31.27 /KW	$ 31.27 /KW	$ 35.96 /KW
POWER CONDITIONING	$ 0.00 /KW	$ 0.00 /KW	$ 0.00 /KW
LOX PRODUCTION	$ 0.00 /KW	$ 0.00 /KW	$ 0.00 /KW
TURBINES & COMPRESSORS	$ 50.75 /KW	$ 50.75 /KW	$ 58.37 /KW
STEAM TURB. & GEN.	$ 0.00 /KW	$ 0.00 /KW	$ 0.00 /KW
INSTRUMENT. & CONTROL	$ 54.80 /KW	$ 54.80 /KW	$ 63.02 /KW
STRUCTURES & PLUMBING	$ 54.80 /KW	$ 54.80 /KW	$ 63.02 /KW
GENERAL FACILITIES	$ 27.62 /KW	$ 27.62 /KW	$ 31.76 /KW
TOTAL	$ 575.61 /KW	$ 644.02 /KW	$ 740.63 /KW

Figure 12. Example of the contingency cost summary screen.

Figure 13 is a representation of the cost summary screen on which all the major cost categories are displayed. The cost module continues after this screen to estimate the costs for industrial depreciation etc. which are not of use in our investigations but must be executed to obtain a proper exit from the program.

PLANT COST SUMMARY		
TOTAL PLANT CAPITAL		$ 712.60 /KW
INSTALLATION COST		$ 213.78 /KW
ENGR & HOME OFFICE		$ 213.78 /KW
PROCESS CONTINGENCIES		$ 68.41 /KW
PROJECT CONTINGENCIES		$ 117.15 /KW
TOTAL PLANT COST	$1,325.73 /KW	
TOTAL PLANT INVESTMENT	$1,453.00 /KW	
START UP COST		
PREPAID ROYALTIES		$ 7.27 /KW
ONE MONTH FIXED OPERATING COST		$ 4.29 /KW
ONE MONTH VARIABLE OPERATING COST		$ 25.51 /KW
START UP COST		$ 66.12 /KW
TOTAL CAPITAL REQUIREMENT		$1,519.12 /KW

Figure 13. Example of cost summary screen.

Determining component and system weights and volumes, WT-VOL7

This module is the culmination of the design efforts of the programs up to this point. It is entered automatically at the conclusion of the ECON module. The operator must first decide what packing factor to use. The default value, and the one almost universally utilized in past studies, is 1.5. This value represents the additional volume required for walkways, maintenance spaces, pipe bends and flanges, and other possible contingencies. Figure 14 represents the first output data screen in a series of four. It contains a summation of the system weight data.

SYSTEM WEIGHT ANALYSIS			
APPLICATION: 1.0 mW NET POWER: 2490.882 KW		OPERATING TIME: 24.0 hrs CELL TYPE: IEMFC	
(TONS)	FUEL CELL (NO2FO)	GAS TURBINE (NO2FO)	DIESEL ENGINE (NO2FO)
POWER SECTION	2.0	25.3	24.4
INVERTER	0.1	N/A	N/A
HEAT EXCHANGERS	1.0	N/A	N/A
B.O.P.	5.9	N/A	N/A
SUBTOT	9.0	25.3	24.4
SPECIFIC WT. lb/kw	8.1	22.9	22.1
FUEL	12.7	13.4	11.8
TOTAL	21.6	38.7	36.2
SPECIFIC WEIGHT (lb/kWh)	0.81	1.46	1.36

Figure 14. Example of system weight summary screen.

The screen containing the system volume summary follows immediately and appears as shown in Figure 15.

SYSTEM VOLUME ANALYSIS			
APPLICATION: 1.0 mW NET POWER: 2490.882 KW		OPERATING TIME: 24.0 hrs CELL TYPE: IEMFC	
(FT3)	FUEL CELL (NO2FO)	GAS TURBINE (NO2FO)	DIESEL ENGINE (NO2FO)
POWER SECTION	140.7	1985.5	1878.2
INVERTER	10.6	N/A	N/A
HEAT EXCHANGERS	69.5	N/A	N/A
B.O.P.	180.8	N/A	N/A
SUBTOTAL	602.4	1985.5	1878.2
SPECIFIC VOL. ft3/kw	0.24	0.80	0.75
FUEL	528.6	557.8	491.2
TOTAL	1131.0	2543.3	2369.4
SPECIFIC VOLUME (in3/kWh)	32.69	73.51	68.49

Figure 15. Example of the system volume summary screen.

The next two screens give weight and volume details of the balance of plant. Figure 16 shows the data display screen for the heat exchangers for the current sample 2500kW sample fuel cell system. In the sample case only two heat exchangers are required. In other cases, as many as nine heat exchangers are required and will be displayed in a similar manner as those shown.

HEAT EXCHANGERS			
	AREA (ft2)	WEIGHT (lbs)	VOLUME (ft3)
HEAT EXCHANGER # 1	3116.2	1306.3	36.2
HEAT EXCHANGER # 2	141.4	971.2	33.4
TOTAL 1- 2		2277.5	69.5

Figure 16. Example of heat exchanger weight and volume analysis.

The balance of plant detailed analysis, as shown in Figure 17, contains data on the balance of plant including the reformer,shift converter, and desulfurizing equipment. The HDS refers to a hydrodesulfurizer unit which is required for some technologies which use steam reforming. It is not required for ATR operation.

BALANCE OF PLANT	AREA (ft2)	WEIGHT (lbs)	VOLUME (ft3)
TOTAL 1- 0		0.0	0.0
REFORMER		3939.9	65.7
SHIFT CONVERTER		6646.9	79.6
HDS		0.0	0.0
ZNO BED		2607.2	35.5

Figure 17. Example of balance of plant weight and volume analysis.

The ZnO beds in this sample run are sized to continuously desulfurize fuel at the maximum rate for the plant assuming a sulfur content of 0.5 percent. They consist of two beds, one processing anode gases while the other in regenerated with a small flow of air. The beds are reversed on a 24 hour cycle.

This is a considered a conservative estimate at this time. Inquiries are being made in the field of new, more efficient adsorption media. More efficient absorbers will lower the associated weight and volume. The new higher standards of air quality are causing refineries to produce ever lower sulfur content in their marketable fuels. By the time fuel cell power systems technology reaches mass production capacity in a few years, these future fuels will also decrease the impact on on-board sulfur removal equipment.

Off-Design Module Operation, DTRC7-OD.

After the design of the fuel cell power system has been completed, the operator may run the off-design module to obtain specific fuel capacities at various loads. This is an independent program which must be run separately. It uses data automatically filed during the running of the design modules. It is best to run this module immediately following DTRC7-R5 so that there will be no question as to the validity of the input data. Figure 18 shows an example of the set-up screen displayed after a net power of 50 percent of full load (1250 kW) is requested.

IEMFC PLANT PERFORMANCE DATA

OVERALL EFFICIENCY	41.9 %		
POWER:			
NET	1250.0 kW	CURRENT DENSITY	442.2 asf
GROSS	1376.4 kW	CELL VOLTAGE	0.786 volts
FUEL CELL	1204.3 kW	OPEN CIRCUIT (dH/nF)	1.227 volts
INVERTER	0.0 kW	CELL AREA	3961.7 ft2
PARASITE	110.6 kW		
UTILIZATION:		HEAT:	
FUEL	0.850		
HYDROGEN	0.850	BURNER	-4.1E+06 btu/hr
OXYGEN	0.710		
TEMPERATURE:			
ANODE INLET	253.5 deg F		
CATHODE INLET	231.4 deg F		
CELL EXIT	238.0 deg F		

Figure 18. Example of the set-up screen for off-design analysis.

Differences in the data between the original design, Figure 6, and the off-design data, Figure 18, are as follows:

- the net power is exactly as requested, half of the full load or 1250 kW
- the efficiency is higher, 41.9 percent compared to 37.7 percent
- temperatures are reduced
- cell voltage is higher due to a lower current density
- oxygen utilization is increased while fuel utilization is held constant

Figure 19 contains the summary of the output data from the off-design program module. The most significant variable is the fuel rate given in pound moles per hour (MPH). Using the average molecular weight of the fuel, 204.19 lb/lb mole for diesel fuel, the specific fuel consumption versus load curve, Figure 1, can be obtained.

OFF-DESIGN NET POWER	1250.00 KW
OFF-DESIGN GROSS POWER	1376.40 KW
OFF-DESIGN OVERALL EFFICIENCY	0.42
DESIGN OVERALL EFFICIENCY	0.38
MECHANICAL EFFICIENCY	0.91
CURRENT DENSITY	442.17 ASF
CELL VOLTAGE	0.79 VOLTS
TOTAL AREA	3961.72 SQ FT
MOLECULAR WT OF FUEL	204.19 LB/LBMOL
FUEL FLOW	2.73 MPH
FC STACK EFFICIENCY	0.64
FC THEORETICAL VOLTAGE	1.23 VOLTS
TAFEL SLOPE	0.06 VOLTS/DECADE
WASTE GATE	0.00
FUEL ADDITION	0.05 MPH

Figure 19. Example of the off-design data summary screen.

The datum referred to as "WASTE GATE" is a programming artifact to allow for energy and material overflow during program operation and is somewhat analogous to a gas by-pass of the stack during transient operation, eg. start-up, shut-down, and load change. It has no meaning at steady-state conditions (Except possibly during completely unloaded conditions).

As the load on a given fuel cell system is reduced the overall thermal efficiency increases, and there is less energy available in the spent anolyte gas to power the turbine. Therefore some fuel must bypass the stack and be mixed with the spent anolyte gas ahead of the burner. The FUEL ADDITION variable refers to the fraction of total fuel representative of the additional energy. This fuel is included in the FUEL FLOW variable and is broken out in the table for analysis purposes.

The TAFEL SLOPE is a variable used in computing the fuel cell polarization curve. It is shown for analytic purposes only and is of limited use in the context of this report.

3-D MODELING BY COMPUTER AIDED DESIGN

At the conclusion of the analytical design programs sufficient data is available to produce three-dimensional models with an appropriate computer aided design (CAD) program. The model shown in Figure 20 was produced using AutoCad™ (release 12) from the data obtained during the sample design and analysis. The model may be combined with other models such as that for a ship, to check the fit

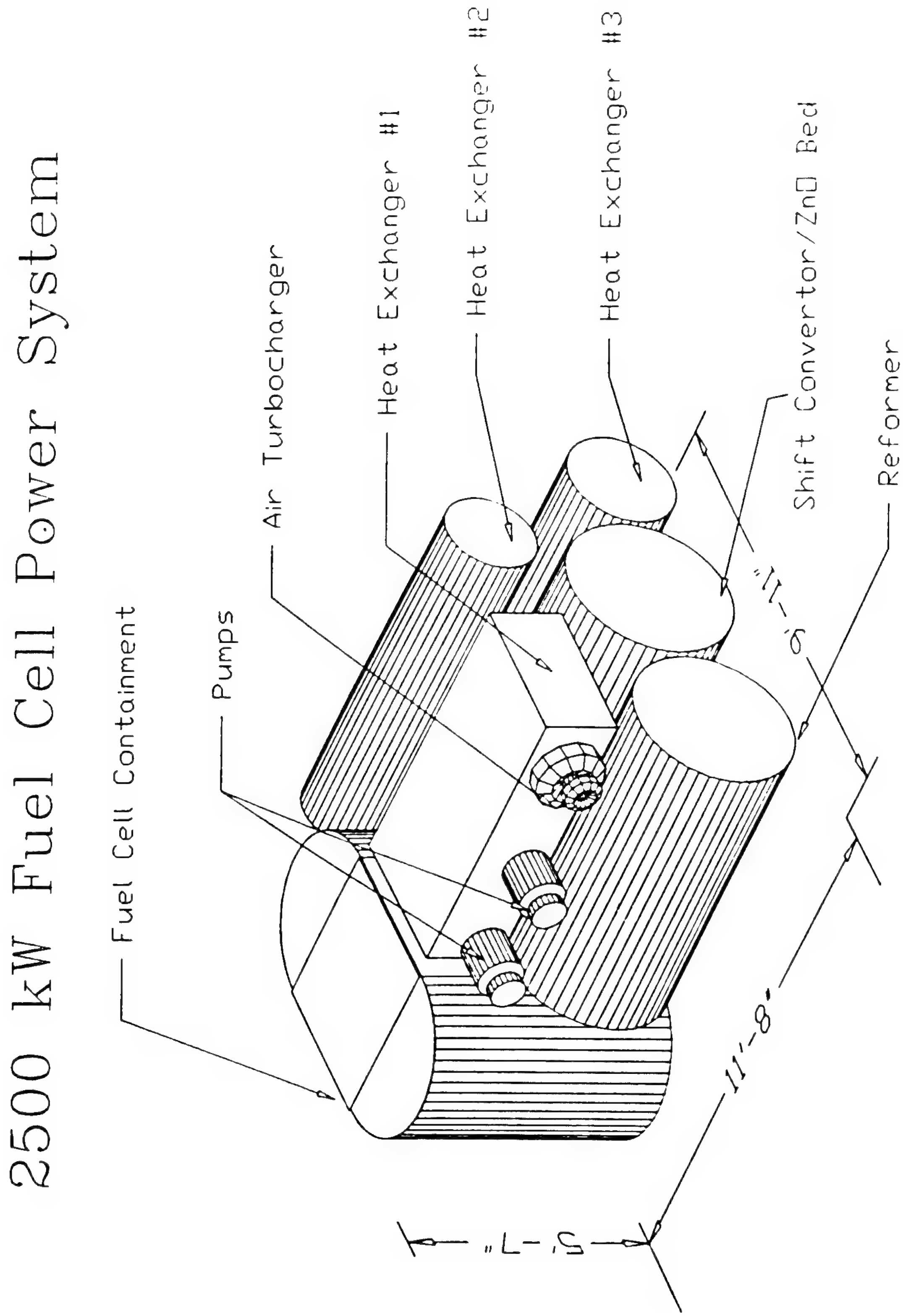

Figure 20. 3-dimensional model of the 2500 kW fuel cell power system.

of components, or to aid in visualizing installations within allotted spaces with the capability to readjust component positions for economy of space. 3-D modeling also allows realistic comparisons of fuel cell systems with other electric power plants.

CONCLUSIONS

The computer modeling programs available at the Annapolis Detachment, Carderock Division,NSWC are extremely versatile and effective in determining the design parameters for PEM, PAFC, and MCFC power systems up to 50 MW. It is very probable that larger power systems can be analyzed without modification although this has not been attempted to date. Although cell components for 10kW stacks have been verified, the BOP of these small power systems, in the range of 10 kW and below, may be suspect as scaling factors for such small equipment are sensitive to unspecifiable form factors, such as the radiant heat losses from an unspecifiable shape, and flow factors in piping which, in actuality, may have numerous acute bends which are unpredictable or at least unspecified.

The programs and modules covered in the above description can be used to obtain the following parametric data for the design of many fuel cell systems:

- Cell design active area
- Stack design including the number of cells, weight, and volume
- Balance of plant weight and volume including;
    - reformer
    - shift converter
    - condensers
    - heat exchangers
    - sulfur adsorbers
    - pumps, blowers, and motors

The heat balance and heat exchanger analysis module is ideal for designing the complex arrays required for realizing the fuel economy fuel cell technology permits. This gives the designer the advantage of concentrating on the aspects of ubiquitous fuel cell system design without having to dilute their efforts with tedious heat balance and heat exchanger design.

The principal caveat revealed in this study is that no diesel fuel powered fuel cell system has been built to date that can be used to validate the results of the programs. Until this is accomplished, all the design data generated with these modules must be considered as theoretical. Only the PAFC module has a been validated against an industrial facsimile. A comparison of the design data from the PAFC module run corresponded well with the design of the ONSI™ PC25, a commercially available 200kW PAFC system using natural gas.

RECOMMENDATIONS

Continuous updating of the existing modules to reflect the ever changing state of the art in fuel cell development is strongly recommended. Examples of these modifications are:

- addition of bottoming cycles to exploit all available energy
- updated data for heat exchanger designs and materials
- optimized heat balance routines for maximizing water recovery.

It is recommended that a contract to generate a design module specific to solid oxide technology be initiated as soon as possible. This would enhance the present effort in assessing and analyzing future systems incorporating this promising technology.

APPENDIX A: Example of PEM design data for ship impact study

POLYMER EXCHANGE TECHNOLOGY FUEL CELL SYSTEMS

CORVETTE 2100 PROPULSION										
Nominal Power, MWatt		9			10			11		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	9043.79	9043.72	9043.71	10047.64	10047.63	10047.63	11053.49	11054.50	11053.51
Air Flow	SCFS	286.26	267.18	250.48	318.04	296.83	296.83	349.87	326.58	306.14
Exhaust Flow	SCFS	299.12	279.18	261.73	332.32	310.17	310.17	365.59	341.25	319.89
Exhaust Temp	Deg. F.	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00
Sea H2O	GPM	1495.12	1395.44	1308.22	1661.08	1550.34	1550.34	1827.36	1705.69	1598.95
Potable H2O	GPM	8.64	8.07	7.56	9.60	8.96	8.96	10.56	9.86	9.24
Cost: Fuel Cell	$ / kW	265.20	312.34	387.88	265.19	312.34	312.34	265.18	312.33	387.89
: BOP	$ / kW	359.57	362.76	346.93	351.00	354.44	354.44	343.56	347.21	358.71
Fuel Cell Wt	Ltons	7.12	8.40	10.44	7.91	9.33	9.33	8.70	10.27	12.76
Fuel Cell Vol	Cu. Ft	759.48	895.61	1113.68	843.77	995.14	995.14	928.16	1094.86	1361.29
BOP Wt	Ltons	13.20	12.61	11.99	14.16	13.52	13.52	15.10	14.41	13.80
Desulfurizer Wt	Ltons	1.39	3.89	3.65	4.63	4.33	4.33	5.10	4.76	4.46
BOP Vol	Cu. Ft.	695.38	665.58	620.41	743.96	711.70	711.70	791.40	756.80	725.91
Desulfurizer Vol	Cu. Ft.	63.85	178.79	167.62	212.82	198.64	198.64	234.13	218.54	204.87
Fuel, 125%	Lb\kW-hr	0.4804	0.4631	0.4460	0.4804	0.4631	0.4631	0.4804	0.4631	0.4460
100%	Lb\kW-hr	0.4633	0.4507	0.4377	0.4633	0.4507	0.4507	0.4633	0.4507	0.4377
75%	Lb\kW-hr	0.4509	0.4418	0.4321	0.4509	0.4418	0.4418	0.4509	0.4418	0.4321
50%	Lb\kW-hr	0.4451	0.4388	0.4316	0.4451	0.4388	0.4388	0.4451	0.4388	0.4316
25%	Lb\kW-hr	0.4585	0.4542	0.4491	0.4585	0.4542	0.4542	0.4585	0.4542	0.4491

CORVETTE 2100 SHIP SYSTEM GENERATOR										
Nominal Power, kWatt		400			500			600		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	401.94	401.94	401.94	502.43	502.43	502.43	602.91	602.91	602.91
Air Flow	SCFS	12.72	11.87	11.13	15.90	14.84	13.92	19.08	17.81	16.70
Exhaust Flow	SCFS	13.29	12.41	11.63	16.62	15.51	14.54	19.94	18.61	17.45
Exhaust Temp	Deg. F.	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00
Sea H2O	GPM	66.45	62.02	58.14	83.06	77.52	72.68	99.67	93.03	87.21
Potable H2O	GPM	0.38	0.36	0.34	0.48	0.45	0.42	0.58	0.54	0.50
Cost: Fuel Cell	$ / kW	265.87	312.98	388.50	265.79	312.91	388.41	265.72	312.84	388.37
: BOP	$ / kW	871.01	860.53	859.18	799.89	791.59	792.19	746.98	740.30	742.36
Fuel Cell Wt	Ltons	0.32	0.37	0.46	0.40	0.47	0.58	0.48	0.56	0.70
Fuel Cell Vol	Cu. Ft	33.77	39.89	49.58	42.24	49.77	61.90	50.71	59.74	74.32
BOP Wt	Ltons	1.81	1.74	1.68	2.06	1.98	1.91	2.29	2.20	2.12
Desulfurizer Wt	Ltons	0.37	0.37	0.37	0.23	0.22	0.20	0.28	0.26	0.24
BOP Vol	Cu. Ft.	84.83	81.36	78.26	97.38	93.26	89.60	109.35	104.62	100.42
Desulfurizer Vol	Cu. Ft.	17.02	17.02	17.02	10.64	9.93	9.31	12.77	11.92	11.17
Fuel, 125%	Lb\kW-hr	0.4804	0.4631	0.4460	0.4804	0.4631	0.4460	0.4804	0.4631	0.4460
100%	Lb\kW-hr	0.4633	0.4507	0.4377	0.4633	0.4507	0.4378	0.4633	0.4507	0.4377
75%	Lb\kW-hr	0.4509	0.4418	0.4321	0.4509	0.4418	0.4321	0.4509	0.4418	0.4321
50%	Lb\kW-hr	0.4444	0.4381	0.4309	0.4444	0.4381	0.4309	0.4452	0.4388	0.4316
25%	Lb\kW-hr	0.4577	0.4534	0.4483	0.4577	0.4534	0.4483	0.4577	0.4534	0.4483

APPENDIX B: Example of PAFC design data for ship impact study

PHOSPHORIC ACID TECHNOLOGY FUEL CELL SYSTEMS

CORVETTE 2100 PROPULSION

Nominal Power, MWatt		9			10			11		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	8610.87	8610.87	8610.87	9567.64	9567.63	9567.64	10524.40	10524.40	10524.40
Air Flow	SCFS	255.74	238.69	223.77	284.15	265.21	248.63	312.57	291.73	273.50
Exhaust Flow	SCFS	268.19	250.31	234.66	297.99	278.12	260.74	327.79	305.93	286.81
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	1905.70	1677.91	1478.60	2117.44	1864.34	1642.88	2329.19	2050.78	1807.17
Potable H2O	GPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cost: Fuel Cell	$ / kW	320.32	458.03	754.77	320.32	458.03	754.76	320.31	458.02	754.76
: BOP	$ / kW	488.21	500.18	558.30	482.83	494.06	556.02	476.41	491.83	550.51
Fuel Cell Wt	Ltons	57.75	82.61	136.19	64.16	91.79	151.32	70.59	100.96	166.46
Fuel Cell Vol	Cu. Ft	4190.17	5994.22	9882.14	4655.35	6660.12	10980.16	5121.71	7326.01	12078.17
BOP Wt	Ltons	31.57	29.01	27.79	34.12	31.09	30.61	35.93	33.74	31.65
Desulfurizer Wt	Ltons	6.97	6.97	6.97	7.48	7.48	7.48	7.97	7.97	7.97
BOP Vol	Cu. Ft.	1834.44	1731.55	1672.82	1939.65	1824.94	1783.95	2021.68	1931.43	1844.36
Desulfurizer Vol	Cu. Ft.	341.67	341.67	341.67	366.95	366.95	366.95	391.48	391.48	391.48
Fuel, 125%	Lb\kW-hr	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680
100%	Lb\kW-hr	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899
75%	Lb\kW-hr	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402
50%	Lb\kW-hr	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896
25%	Lb\kW-hr	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245

CORVETTE 2100 SHIP SYSTEM GENERATOR

Nominal Power, kWatt		400			500			600		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	382.71	382.71	382.71	478.38	478.38	478.38	574.06	574.06	574.06
Air Flow	SCFS	11.37	10.61	9.95	14.21	13.26	12.43	17.05	15.91	14.92
Exhaust Flow	SCFS	11.92	11.12	10.43	14.90	13.91	13.04	17.88	16.69	15.64
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	84.70	74.57	65.72	105.87	93.22	82.14	127.05	111.86	98.57
Potable H2O	GPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cost: Fuel Cell	$ / kW	320.61	458.31	755.03	320.58	458.27	755.00	320.55	458.25	754.98
: BOP	$ / kW	868.08	870.80	919.24	813.40	818.12	867.79	776.15	782.01	831.62
Fuel Cell Wt	Ltons	2.57	3.68	6.05	3.22	4.60	7.57	3.86	5.52	9.08
Fuel Cell Vol	Cu. Ft	186.54	266.83	439.21	233.77	334.13	549.01	279.82	400.24	658.81
BOP Wt	Ltons	4.15	4.03	3.66	4.59	4.31	4.19	4.97	4.81	4.63
Desulfurizer Wt	Ltons	0.80	0.80	0.79	0.94	0.94	0.93	1.07	1.07	1.06
BOP Vol	Cu. Ft.	308.17	299.71	268.30	340.44	318.66	310.64	366.38	355.95	343.42
Desulfurizer Vol	Cu. Ft.	38.99	38.89	38.79	45.72	45.58	45.46	52.07	51.91	51.77
Fuel, 125%	Lb\kW-hr	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680
100%	Lb\kW-hr	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899
75%	Lb\kW-hr	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402
50%	Lb\kW-hr	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896
25%	Lb\kW-hr	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245

APPENDIX C: Example of MCFC design data for ship impact study

MOLTEM CARBONATE TECHNOLOGY FUEL CELL SYSTEMS

		DESTROYER 5299 PROPULSION						6 ATM PRESSURE		
Nominal Power, MWatt		16			18			20		
Cell Design Voltage		0.65	0.70	0.75	0.65	0.70	0.75	0.65	0.70	0.75
Net Power	kWatts	16000.00	16000.00	16000.00	18000.00	18000.00	18000.00	20000.00	20000.00	20000.00
Air Flow	SCFS	662.98	628.32	605.33	745.85	706.86	681.00	828.72	785.40	756.67
Exhaust Flow	SCFS	670.99	635.96	612.65	754.87	715.45	689.23	838.74	794.95	765.81
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	5426.30	4925.70	4601.90	6104.60	5541.20	5177.10	6782.90	6156.60	5752.40
Potable H2O	GPM									
Cost: Fuel Cell	$ / kW	80.66	90.14	106.11	80.66	90.14	106.11	80.66	90.14	106.11
: BOP	$ / kW	512.67	469.92	480.04	512.67	470.41	481.60	512.67	470.41	483.16
Fuel Cell Wt	Ltons	223.46	250.58	10560.20	251.38	281.90	330.73	279.31	313.23	368.80
Fuel Cell Vol	Cu. Ft	8212.99	9209.46	10804.15	9239.61	10360.52	12154.57	10266.22	11511.58	13504.99
BOP Wt	Ltons	47.38	44.78	42.38	52.98	50.02	47.44	58.57	55.25	52.49
Desulfurizer Wt	Ltons	13.88	13.74	13.87	15.49	15.33	15.47	17.10	16.92	17.07
BOP Vol	Cu. Ft.	2470.07	2231.34	2210.39	2729.26	2467.81	2431.42	2988.45	2704.28	2652.46
Desulfurizer Vol	Cu. Ft.	946.37	940.65	953.33	1055.34	1048.88	1062.59	1164.31	1157.11	1171.86
Fuel, 125%	Lb\kW-hr	0.62	0.62	0.62	0.62	0.59	0.55	0.62	0.59	0.55
100%	Lb\kW-hr	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206
75%	Lb\kW-hr	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244
50%	Lb\kW-hr	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275
25%	Lb\kW-hr	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960

		DESTROYER 5200 SHIP SYSTEM GENERATOR								
Nominal Power, kWatt		2300			2500			2700		
Cell Design Voltage		0.65	0.70	0.75	0.65	0.70	0.75	0.65	0.70	0.75
Net Power	kWatts	2300.00	2300.00	2300.00	2500.00	2500.00	2500.00	2700.00	2700.00	2700.00
Air Flow	SCFS	95.30	90.34	87.02	103.59	98.19	94.58	111.88	106.05	102.15
Exhaust Flow	SCFS	96.46	91.42	88.07	104.84	99.37	95.73	113.23	107.32	103.38
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	780.00	709.70	661.40	847.80	771.20	719.00	915.60	832.80	776.50
Potable H2O	GPM									
Cost: Fuel Cell	$ / kW	80.66	90.14	106.11	80.66	90.14	106.11	80.66	90.14	106.11
: BOP	$ / kW	512.67	469.92	467.57	512.67	470.41	467.57	512.67	470.41	467.57
Fuel Cell Wt	Ltons	32.16	36.02	1428.28	34.95	39.15	45.93	37.74	42.28	49.61
Fuel Cell Vol	Cu. Ft	1180.70	1324.70	1553.76	1283.36	1439.80	1688.80	1386.02	1554.91	1823.85
BOP Wt	Ltons	9.04	8.95	7.77	9.60	9.47	8.27	10.16	10.00	8.78
Desulfurizer Wt	Ltons	2.85	2.83	2.90	3.01	2.99	3.06	3.17	3.15	3.22
BOP Vol	Cu. Ft.	694.61	611.50	696.30	720.53	635.15	718.40	746.45	658.80	740.51
Desulfurizer Vol	Cu. Ft.	199.94	199.25	204.85	210.84	210.07	215.78	221.73	220.90	226.71
Fuel, 125%	Lb\kW-hr	0.62	0.62	0.62	0.62	0.59	0.55	0.62	0.59	0.55
100%	Lb\kW-hr	0.46	0.44	0.42	0.46	0.44	0.42	0.46	0.44	0.42
75%	Lb\kW-hr	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244
50%	Lb\kW-hr	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275
25%	Lb\kW-hr	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960

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